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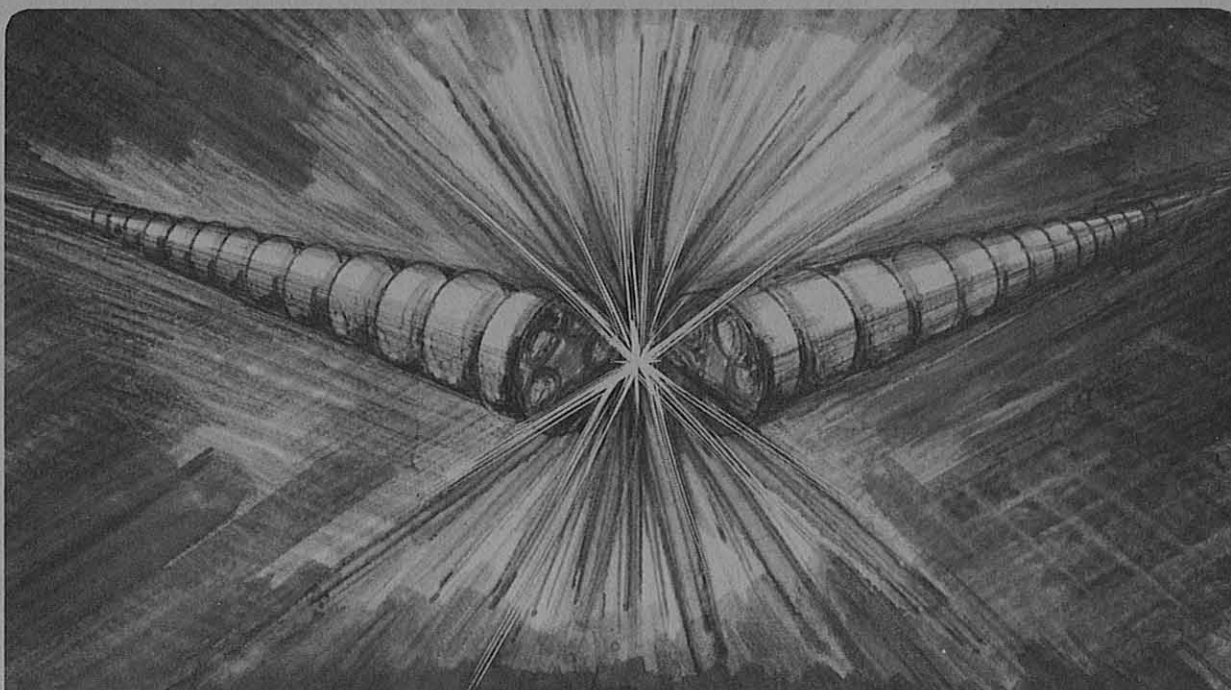
## Accelerator & Fusion Research Division

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### **THE EFFECTS OF FILAMENT MAGNETIZATION IN SUPERCONDUCTING MAGNETS AS CALCULATED BY POISSON**

S. Caspi, W.S. Gilbert, M. Helm, and L.J. Laslett

September 1986



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**Abstract**

Magnetization of superconducting material can be introduced into POISSON through a field dependent permeability table (in the same way that iron characteristics are introduced). This can be done by representing measured magnetization data of the increasing and decreasing field by two independent B- $\gamma$  curves ( $\gamma = 1/\mu$ ).

Magnetization curves of this type were incorporated into the current regions of the program POISSON and their effect on the field coefficients observed. We have used this technique to calculate the effect of magnetization on the multipole coefficients of a SSC superconducting dipole magnet and to compare these coefficients with measured values.

**Introduction**

Magnetostatic problems solved by POISSON employ current and air regions as well as regions of non-linear permeable iron. It is customary to set the permeability of the current regions identical to that of air (e.g.  $\mu = 1$ ) and introduce a permeability table (e.g. B-H) for the iron regions. If the conductor is made of a superconducting material, setting the permeability of the current regions equal to that of air is only an approximation. The existence of surface and bulk supercurrents, which partially shield the superconductor's interior from the penetrating field, results in the superconductor acquiring a magnetization that in some cases cannot be ignored. Magnetization in superconducting dipole magnets influences the field uniformity. This effect is quite small at high fields ( $H \gg H_p$ ;  $H_p$  = field at penetration) but introduces large harmonic coefficients at low fields where the magnitude of the magnetization is of the order of the applied field.

The method outlined here takes advantage of available experimental data for the conductor magnetization, integrating them into the relaxation process in POISSON and thereby avoiding some of the possible inaccuracies introduced by perturbation techniques such as the method proposed by G. Morgan (BNL) Ref. 1, using the program GFUN. An analytical approach for introducing magnetization effects into superconducting magnets has been used by M. Green (LBL) Ref. 2.

We present two examples. The first is an analytical example, using a linear and reversible magnetization curve, which is compared with the POISSON solution. The second is a more realistic case where a measured magnetization curve of a superconducting cable is introduced into POISSON and results are compared with measurements of a model SSC dipole magnet.

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**Example 1 - Magnetization of a Current Carrying Annulus**

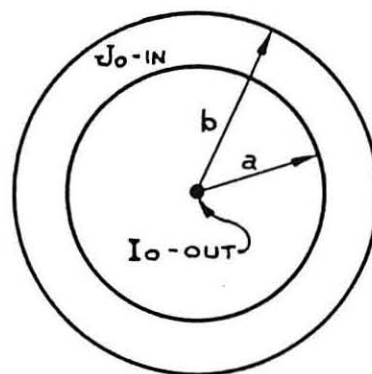
**Analytical Solution**

We first analyze an arrangement (sketched below) in which a current  $I_0$  flows, with constant current density, into an annulus of inner and outer radii  $a, b$  and returns as  $I_0$  through the annulus center. We make use of relations:

$$\oint H d\ell = \frac{4\pi}{10} I$$

$$B = \mu_r H$$

$H$  = Oersted  
 $\ell$  = cm  
 $I$  = Amp  
 $B$  = Gauss



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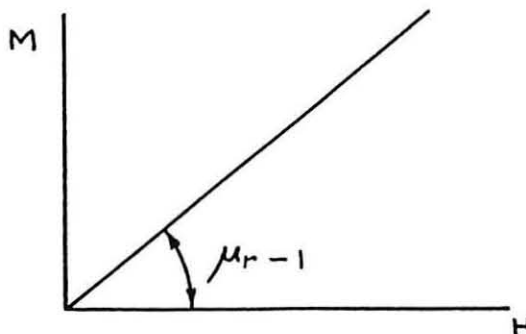
Then, for  $r < a$ ,  $H_\theta = \frac{2I_0}{10r}$ ;

For  $b > r > a$ ,  $I = I_0 \frac{b^2 - r^2}{b^2 - a^2}$

$$H_\theta = \frac{2I_0}{10} \frac{b^2 - r^2}{r(b^2 - a^2)}$$

and for  $r > b$ ,  $H_\theta = 0$ .

If  $\mu_r \neq 1$  in the annulus, then  $B \neq H$  ( $B = H + 4\pi M$ ) corresponding to a magnetization curve sketched below.  $\mu_r = 1$  in all other regions.



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We now derive the vector potential  $A$ , using  $B_\theta = -\partial A/\partial r$ , so that it can be compared directly with POISSON's output.

For  $r > b$ : Since  $A = \text{constant}$ , we choose  $A = 0$ .

For  $b > r > a$ :

$$A = \frac{2I_0}{10} \mu_r \left[ \frac{b^2}{b^2 - a^2} \ln \frac{b}{r} - \frac{1}{2} \frac{b^2 - r^2}{b^2 - a^2} \right]$$

For  $r < a$ :

$$A = \frac{2I_0}{10} \left[ \mu_r \left( \frac{b^2}{b^2 - a^2} \ln \frac{b}{a} - \frac{1}{2} \right) - \ln \frac{r}{a} \right]$$

If we select  $a = 1$  cm,  $b = 2$  cm, and  $I_0 = 4000$  Amp, we calculate:

$$\begin{aligned} r \geq 2 & \quad A = 0 \\ 1 \leq r \leq 2 & \quad A = 800 \mu_r \left[ \frac{4}{3} \ln \frac{2}{r} - \frac{4 - r^2}{6} \right] \\ r \leq 1 & \quad A = 800 \left[ \mu_r 0.424196 - \ln r \right] \end{aligned}$$

In Table I below we compare numerical results for

$\mu_r = 0.5$  and  $1.5$ .

Table I

$\mu_r$	$r$ (cm)	$A$ , analytical	$A$ , Poisson	$\Delta\%$
0.5	0.5	724.20	723.3	0.12
	1.0	169.68	169.28	0.24
	1.5	36.76	36.6	0.45
1.5	0.5	1063.55	1062.3	0.12
	1.0	509.04	508.15	0.17
	1.5	110.29	110.0	0.26

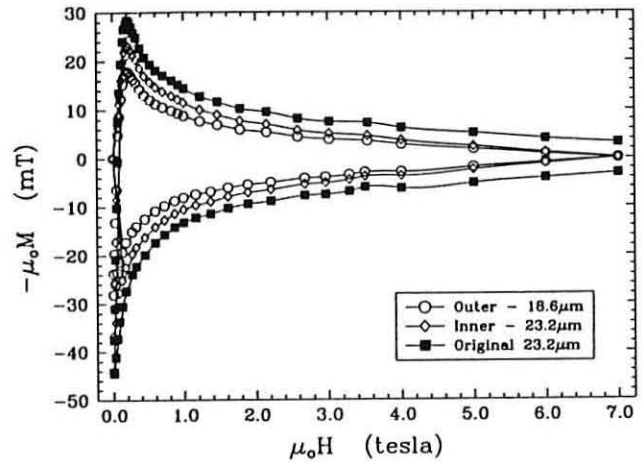
Example 2 - Magnetization of a Superconducting Dipole Magnet

#### Method and Application

We construct two groups of input tables for POISSON (no more than 3 per group, as POISSON can handle only a maximum of 3 input tables in addition to the permanent iron table imbedded in the code) to describe the magnetization of superconductor cables used in a dipole magnet. One group of tables includes all magnetization curves, of various cable types, during an increasing field and the other provides similar curves for a decreasing field.

We require magnetization curves for the same cables used in this magnet in order to take care of variations in strand size, copper to superconductor ratio, transport current, and critical current. The magnetization curve of an entire block and not of a single turn (or cable) will be required to take care of insulation, cable compactness, small wedges, and other non-magnetic materials, since current regions in POISSON are usually represented by a single block rather than by a collection of individual turns.

In many cables, measured magnetization data may not be available and then the use of scaling may be required. The magnetization curve should be available over a range of field extending to values as high as the short-sample limit. A detailed example that transforms measured magnetization data into a suitable POISSON input table is given in Ref. 3.



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Fig. 1 Some of the scaled magnetization curves used in the present calculations. The original data were measured by A.K. Ghosh, BNL, and adjusted as described in the Appendix of Ref. 3.

#### Magnet Cross Section

We compared the measured and POISSON-derived multipoles due to residual currents for two SSC dipole cross-sections. The first type, C5, is a 3 wedge cross-section (Fig. 2a) and the second type, NC515, is a 4 wedge cross-section (Fig. 2b), Ref. 4. The features common to both cross-sections are listed below.

The inner and outer layers of the 4-cm bore two-layer magnet (Fig. 2) are made of a 23-strand and a 30-strand cable respectively, with 1.3 and 1.8 Cu/sc ratios. Stainless-steel collars over the

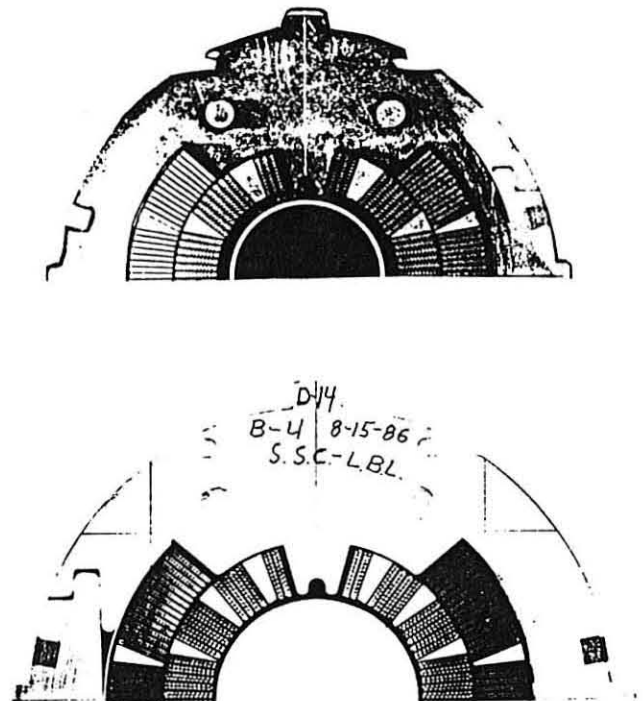


Fig. 2 A half cross-section for the C5 3 wedge design (a), and of the NC5154 wedge design (b).

outer layer result in a coil-iron gap of approximately 15 mm. We have ignored possible saturation of the iron and therefore set the iron permeability to  $\mu = \infty$  in these studies of magnetization effects. We plan that the effect of images in iron of variable permeabilities will be checked in later work. Each individual layer has been subdivided in the computations into two parts of equal radial thickness in order to incorporate the radial dependency of the current density and magnetization.

At the time this work was carried out only magnetization measurements for the inner layer cable were available to us. Such data took into account the existence of copper and superconductor only. We therefore took the steps necessary to scale this single magnetization curve so as to reflect the physical conditions in each of the sublayers as they exist during magnet operation. The full details of the calculations are in Ref. 3.

## Results

A series of POISSON runs was made (total of 32) to produce data in the range of 0.1 T to 6.8 T. The first half of the runs used magnetization tables corresponding to an increasing current, and the remainder, for the same field interval, used magnetization tables for decreasing current. At each field level we obtained two solutions such that upon subtracting their vector potential values we were left with a vector potential that corresponds to the total field change due to magnetization effects. The differential field harmonics (up minus down) were calculated for the dipole and are plotted in Fig. 3. The harmonics  $b_2$ ,  $b_4$ ,  $b_6$ ,  $b_8$  are plotted in Figs. 4a-d (all harmonic calculations were performed at 1 cm radius). These results agree with those computed by M.A. Green<sup>5</sup> using the same magnetization curves and the program SCHAG4. The differences between computed and measured multipoles vary from a few percent for the 6 pole (Fig. 4a), to a factor of 2 for the 18 pole (Fig. 4d).

An interesting observation can be made concerning the magnetization contribution to the 14 pole (Fig. 4c). In the 4-wedge cross-section (NC515) both the computed and measured values of  $b_6$  have reversed their direction for the increasing or decreasing field compared with the 3-wedge cross-section (C5). One can speculate that a cross-section exists that suppresses the magnetization contribution to some of the multipoles.

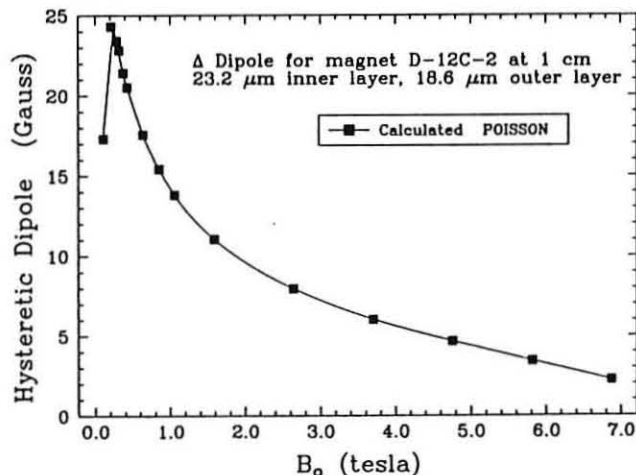


Fig. 3. Differential dipole component (up minus down) due to magnetization.

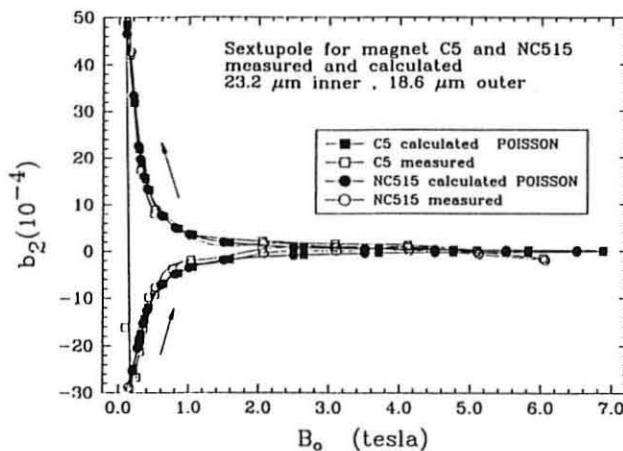


Fig. 4a - 6 pole

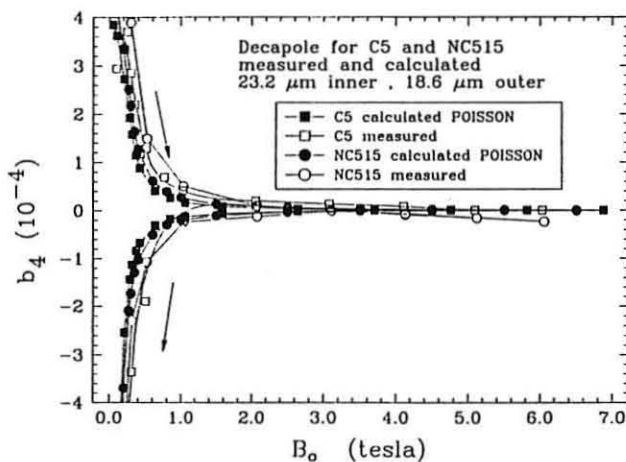


Fig. 4b - 10 pole

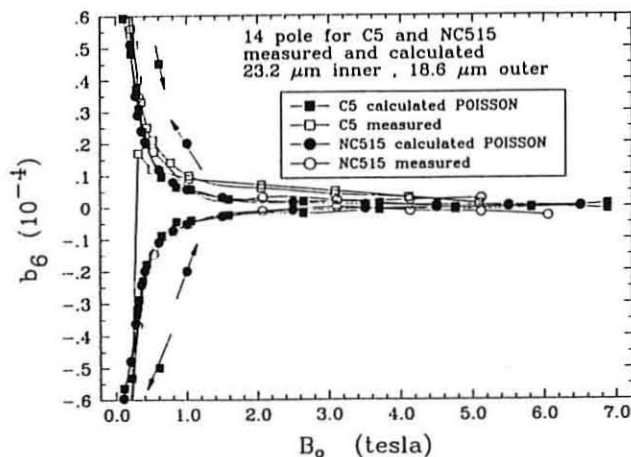


Fig. 4c - 14 pole

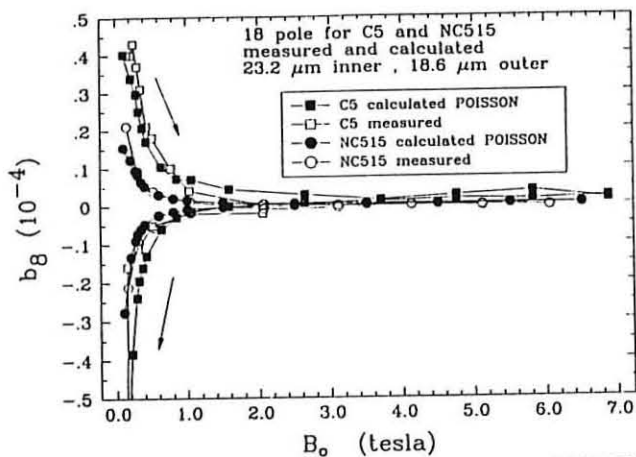


Fig. 4d - 18 pole

Fig. 4. Computations and measurements of the first 4 allowed multipoles due to residual currents.

The capabilities of POISSON to compute the vector potential due to magnetization alone can be used to highlight regions of significant contributions (Fig. 5). Such contributions, reflected as line density, are greater at low field (injection at 0.28 Tesla, Fig. 5a), than at high field (3.7 Tesla, Fig. 5b). Obviously the relative magnetization contributions become insignificant at higher fields.

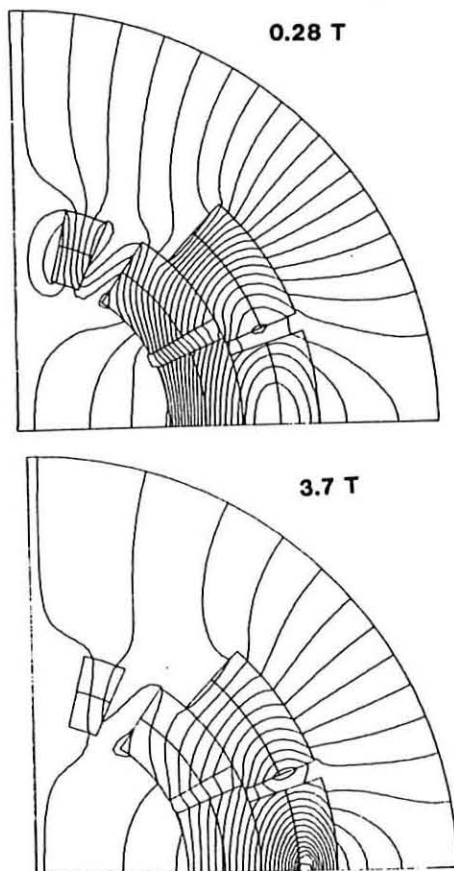


Fig. 5. Flux lines due to magnetization only, at various field levels, produced by subtracting the vector potential which includes magnetization from the one that has zero magnetization.

## Discussion

The magnetic multipoles in SSC model magnets have been successfully computed through an introduction of measured superconductor magnetization data into the field calculation program POISSON. Multipole components for future SSC dipoles (or quadrupoles) using various possible superconductors can be predicted with confidence through this procedure. Running of magnetization tests on small samples of conductor and incorporation of the results into computations is relatively rapid and economical compared with the production and testing of full dipoles.

Certain simplification had to be introduced into the magnetization curves before they could be reduced into a table suitable for POISSON. Specifically there is a sharp transition from positive to negative magnetization, at low fields below 0.1 Tesla, when the field changes direction (turns from decreasing to increasing). The approximation that allowed POISSON to run properly was to have the magnetization go to zero at zero field linearly from the measured values at 0.1 Tesla. This introduced only a small error between the calculations and the magnet measurements for fields above 0.1 Tesla, which is our region of interest.

## Acknowledgments

Supplied by the LBL Magnetic Measurement Group led by M.I. Green, an enormous amount of precise magnetic measurement data is incorporated in the work above. We also wish to acknowledge the discussions and shared ideas of E. Fisk and M. Kuchnir of FNAL that lead into this work. The LBL Superconducting Magnet Group, led by C. Taylor, built and tested the SSC models referred to above.

## References

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5. M.A. Green, Paper L8-8, this conference.